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A New Dynamic Pressure Source for the Calibration of Pressure Transducers

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[2] Located at Boulder, Colorado 80302.

# A New Dynamic Pressure Source for the Calibration of Pressure Transducers

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FOREWORD

The work described was performed as a task within the Electro-mechanical Transducer Project. This is a continuing project for the development of calibration and evaluation methods for electromechanical transducers, supported by a number of Government agencies. This task was funded by the National Aeronautics and Space Administration through the Langley Research Center under order number L-88319.

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A NEW DYNAMIC PRESSURE SOURCE FOR
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A New Dynamic Pressure Source for the Calibration of Pressure Transducers

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A dynamic pressure source is described for producing sinusoidally varying pressures of up to 34 kPa zero-to-peak, over the frequency range of approximately 50 Hz to 2 kHz. The source is intended for the dynamic calibration of pressure transducers and consists of a liquid-filled cylindrical vessel, 11 cm in height, mounted upright on the armature of a vibration exciter which is driven by an amplified sinusoidally varying voltage. The transducer to be calibrated is mounted near the base of the thick-walled aluminum tube forming the vessel so that the pressure-sensitive element is in contact with the liquid in the tube. A section of the tube is filled with small steel balls to damp the motion of the 10-St dimethyl siloxane working fluid in order to extend the useful frequency range to higher frequencies than would be provided by an undamped system.

The dynamic response of six transducers provided by the sponsor was evaluated using the pressure sources; the results of these calibrations are given.

Key words: calibration; dynamic; dynamic calibration; dynamic pressure; dynamic pressure source; liquid column; pressure; pressure source; pressure transducer; sinusoidal pressure; transducer.

1. INTRODUCTION

Increased use of electromechanical transducers for measurement of dynamic pressures in complex processes arising in diverse fields has increased the importance of determining the dynamic characteristics of such transducers. Dynamic pressure-calibration systems now in existence do not meet all the amplitude or frequency range requirements of present technology.

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In 1971 the National Bureau of Standards Instrumentation Applications Section* developed a method for generating sinusoidally varying pressures constant in amplitude within +5% over a frequency range of a few Hertz to about 1 kHz [1]**. In the current work, this method has been modified and extended [2, 3] in both amplitude and frequency capability to result in a source of sinusoidally varying pressures of up to 34 kPa zero-to-peak (about 5 psi zero-to-peak), over the frequency range of approximately 50 Hz to 2 kHz. The source is intended for the dynamic calibration of pressure transducers and consists of a liquid-filled cylindrical vessel, 11 cm in height, mounted upright on the armature of a vibration exciter which is driven by an amplified sinusoidally varying voltage. The transducer to be calibrated is mounted near the base of the thick-walled aluminum tube forming the vessel so that the pressure-sensitive element is in contact with the liquid in the tube. A section of the tube is filled with small steel balls to damp the motion of the 10-St dimethyl siloxane working fluid in order to extend the useful frequency range to higher frequencies than would be provided by an undamped system. Both the natural frequency and the degree of damping of the combined liquid-column-and-transducer structure determine the useful upper frequency limit.

2. EXPERIMENTAL DEVELOPMENT OF SOURCE

2.1 Theoretical Considerations

For the geometry described, both the amplitude of the sinusoidally varying pressure and the natural frequency of the liquid column may be calculated to first approximations by simple relations to permit comparison with experimental results.

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* The Section is now the Components and Applications Section.
**Figures in brackets indicate the literature references listed in section 7.

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Damping is also an important consideration because a damped
system may have a higher useful frequency range than the same
system undamped. With an undamped, single-degree-of-freedom
system, the amplitude-frequency response remains constant within
+5% up to approximately 20% of the natural frequency. In a sys-
tem with optimum damping (a damping ratio of about 0.6 of criti-
cal), the amplitude-frequency response remains constant within
+5% to about 80% of the natural frequency [3,4]. To maintain
a flat response to 2 kHz thus requires an undamped system with a
natural frequency of 10 kHz, an optimally damped system with a
natural frequency of 2.5 kHz, or a non-optimally damped system
with a natural frequency between 2.5 and 10 kHz, with the exact
natural frequency required dependent on the degree of damping.

2.1.1 Pressure Amplitude - The factors that in combination
determine the pressure levels attainable over the frequency range
of interest are (1) the force and displacement capabilities of
the vibration exciter, (2) the density of available working fluids,
(3) the height of the liquid column, and (4) the degree of damping.
This last factor interacts with the others and depends on geometry,
on the bulk modulus and viscosity of the fluid. As noted above,
damping need not be considered at frequencies below about 20% of
the system natural frequency because the amplitude-frequency re-
sponse is flat up to this limit. Up to the stated limit, the
amplitude of the sinusoidal pressure generated within the liquid
column and acting on the transducer is given by [1].

$$P = ah_c\rho$$

where

P = pressure (Pa zero-to-peak),
a = acceleration amplitude (g_n zero-to-peak[*]),
h_c = liquid-column height above the center of the
transducer diaphragm (m), and
ρ = density of liquid (kg/m^3).

As an example, for the source to be described in this paper, h_c =
0.1m and ρ = 972 kg/m^3. At an acceleration of 36 g_n zero-to-peak,
the pressure is calculated to be 34 kPa zero-to-peak, and at 20 g_n
zero-to-peak, 19 kPa.

2.1.2 Natural Frequency - The natural frequency of a liquid
column is directly proportional to the square root of the velocity
of sound in the liquid and inversely proportional to the height of

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[*]The symbol g_n represents the unit of acceleration equal to the
standard value of the acceleration of gravity at the earth's surface.

the column. For an infinitely stiff, open-topped vessel containing the liquid, the system has one degree of freedom with a natural frequency given by [1]

$$f_n = 0.25 \frac{1}{h} \left(\frac{B}{\rho} \right)^{1/2},$$

where

   f_n = natural frequency (Hz),
   h = total height of liquid column (m), and
   B = bulk modulus (Pa).

The quotient of B and ρ is proportional to the velocity of sound in the liquid. For the dynamic pressure source, h = 0.11 m and B = 9.47 x 10^8 Pa, the value given by the supplier for 10-St dimethyl siloxane. The undamped natural frequency is calculated to be 2.24 kHz.

In practice the tube is not infinitely stiff, but has some elasticity. For other than thin-walled vessels, a volume change in the tube itself is usually small enough compared to other volume changes that it may be neglected for practical calibrations. More importantly, the transducer diaphragm forms part of the tube wall, and since this diaphragm is displaced in response to pressure, an overall volume change occurs. The effect of this change is to lower the natural frequency as the effective bulk modulus is reduced. The effective bulk modulus may be defined by the relation [1]

$$B' = \frac{V}{\frac{V}{B} + dV_t},$$

where

   B' = effective bulk modulus (Pa),
   V = volume of liquid in the tube (m^3), and
   dV_t = change of volume resulting from unit pressure change (m^3/Pa).

As an example, transducer B introduces a volume change of 9.14 x 10^{-15} m^3/Pa, as calculated from information supplied by the manufacturer. With this transducer installed in the source, the effective bulk modulus is calculated to be 7.03 x 10^8 Pa and the natural frequency is lowered to 1.93 kHz.

In the source, steel balls are used for damping and the volume of the liquid is reduced by an amount equal to the total volume of the balls, although the column height remains unchanged. As an example, consider that 15% of the volume of the liquid is replaced by the balls (as was done in some of the experiments). The effective

bulk modulus would then be given by 6.73 x 10^8 Pa, and the undamped natural frequency would become 1.89 kHz. If the balls were to occupy 50% of the available volume, the calculated natural frequency would be 1.72 kHz, which is significantly lower than the 2-kHz goal.

Combining the results of the above discussion, the natural frequency is given by

$$f_n = 0.25 \frac{1}{h} \left[\frac{B(V_c - V_b)}{\rho(V_c - V_b + BdV_t)} \right]^{\frac{1}{2}}$$

where

V_c = volume available for liquid with no balls present (m^3),
V_b = volume occupied by balls (m^3), and
h, B, ρ, and dV_t are as given above.

2.2 Preliminary Investigations

Preliminary experiments described in the progress reports [3] were conducted to investigate approaches for improving the frequency range of the method developed earlier. These experiments involved a variety of working liquids, including water, tetrabromoethane, petroleum oils, a fluorocarbon liquid, dimethyl siloxane liquid of various viscosities, glycerine, and mercury. These candidate liquids were chosen because of specific physical properties given in table 1 and on the basis of experience. Chemical reactivity and the criterion of ready availability also governed the choice of liquids. For example, water was chosen because it has a relatively high bulk modulus and because its use in the earlier work permitted intercomparison of experimental results. Tetrabromoethane, the fluorocarbon liquid, and especially mercury have high densities and therefore should confer high-pressure capability with short columns of liquid. Mercury has been used in related work with a closed-tube dynamic pressure source [5]. Dimethyl siloxane liquids and petroleum oils are available in a wide range of viscosities; glycerine possesses a combination of high viscosity and high bulk modulus.

The damping provided by a number of column geometries was also investigated experimentally with the various liquids, as shown in table 1. Among these experiments, which were designed to increase the available wetted surface compared to that of the interior of a simple tube, were trials with columns of various cross-sections (including columns with vertical fins, spiral fins, and multiple channels) and with columns packed with various materials (including bundles of small-diameter tubes, sintered metal filters, and sea sand). A selection of columns is shown in figure 1. Damping of a magnetic liquid by means of a coil electromagnet wound around the outside of the column was also attempted.

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The results of these investigations tended to single out 10-St dimethyl siloxane as the liquid possessing the best combination of properties, including handling quality, of those liquids tried. The principal reasons for rejecting the other liquids may be summarized as follows: water and tetrabromoethane -- low viscosity precludes achievement of effective damping; petroleum oils -- viscosity is highly temperature dependent; fluorocarbon liquid -- bulk modulus too low; glycerine -- presence of dissolved gas (which could not be removed reliably by the vacuum filling procedures described in an earlier report [3] reduced bulk modulus to too low a value; and mercury -- viscosity too low.

2.3 Background for Use of Steel Balls as Column Packing

At an early stage of the work, the use of a material such as sea sand had been proposed as a means of increasing the column wetted surface, and hence the degree of damping, by a very large factor. However, experimental difficulties and inconclusive results discouraged further work along these lines at the time. The comparative success achieved with a column packed with small tubes (inside diameter 0.16 cm) and filled with 10-St dimethyl siloxane encouraged a search for other geometries offering still greater wetted surface (without the insuperable filling problems which had precluded the use of tubes substantially smaller than 0.16 cm i.d.). The use of small objects as a column packing was again considered, with the requirement that the objects not absorb or be soluble in the dimethyl siloxane. If suitable objects could be found in a selection of sizes, a range of wetted areas would be available for experiment. The polished steel balls produced for use in ball bearings are readily available in a range of sizes and do not interact with dimethyl siloxane, and were therefore tried as a column packing. These trials (described in 2) were successful in that the project goals for the source were met (sinusoidally varying pressures of at least 34 kPa zero-to-peak, flat to within ±5% from approximately 50 Hz to 2 kHz), and development of the source was considered complete for the intended purposes.

2.4 Design and Description of Dynamic Pressure Source

An overall view of the dynamic pressure source and associated instrumentation is shown in figure 2. Mounted on the armature of the vibration exciter (C) is the source column (A) with the reference transducer (B) screwed into the base. The position for the transducer to be calibrated is on the opposite side of the column from (B) and is not shown. The controller (D) for the vibration exciter supplies the driving signal and can be programmed to sweep over the frequency range of interest at constant acceleration, displacement, or velocity. The vibration exciter system has a displacement capability of 1.3 cm peak-to-peak and can impart accelerations of 25 g_n to an 11-kg mass at frequencies of 30 Hz and above.

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A digital voltmeter (E) may be switched to read the output of the test transducer, the reference transducer, or the accelerometer mounted in the armature of the vibration exciter. Transducer excitation power supplies are denoted by (F) and (G), and (H) is the accelerometer amplifier. Pressure transducer output as a function of frequency is displayed on the oscilloscope (I), which is equipped with a recording camera.

2.4.1 Column Design - In order to accommodate the ball packing, the column required modification with respect to earlier columns used. The following considerations governed the design: (1) the balls must not be allowed to contact and thus damage the transducer diaphragm, (2) the balls must not be permitted to move in relation to one another or to the column to any significant degree (ball movement would result in uncontrolled changes in damping), (3) a method for conveniently varying the ball loading (ball size and number) is required, and (4) the amount of liquid displaced by the balls should not be so great as to lower the natural frequency below acceptable limits, that is, as shown in 2.1.2, the balls should occupy less than half of the available volume.

The design that was selected utilized pierced circular plates to clamp the balls in a section of the bore near the bottom of the column. The geometry of the plates was subject to the following considerations: (1) the plates should have the maximum practicable amount of open area so as not to impede the movement of the dimethyl siloxane liquid (thus not to change the damping characteristics or the natural frequency appreciably), (2) the holes should be small enough to retain the smallest balls envisaged, (3) the distance between the holes should be less than the diameter of the smallest ball envisaged (to prevent balls from blocking all the holes), and (4) the plates should be thick enough to provide adequate rigidity.

2.4.2 Column Description - The construction that was chosen to satisfy the varying requirements is shown in a cross-sectional sketch, figure 3. Steel balls (K) are clamped tightly in place by two 0.48-cm-thick pierced steel plates (L). The outer diameter of the plates loosely fits the inner diameter of the aluminum column; forty-five 0.13-cm-diameter holes drilled through each plate perpendicular to the faces account for approximately one-third of the face area and provide for free movement of the liquid. The bottom plate rests on a machined shoulder 1.6 cm above the bottom of the column bore. The top plate clamps down on the ball packing, the clamping force being transmitted to the plate from a vented, threaded plug (M) by means of a brass retainer tube (N) which is a loose fit in the main bore (J). This tube has an outside diameter of 1.6 cm and a 0.16-cm wall thickness. The plug engages threads machined into an upper section of the bore. The volume of the column bore available for ball packing may be adjusted through the use of retainer tubes of various lengths combined with

various positions of the threaded plug. Threaded holes for mounting the reference transducer (B) and the transducer to be calibrated (O) are provided in two machine flats near the base of the column. The centerline of these holes is 1 cm above the bottom of the bore. The column is fastened to the vibration exciter armature by means of four machine screws passing through holes (not shown) in the column flange.

2.4.3 Tests to Determine Column Packing and Source Repeatability - The output of reference transducer E was used to determine an acceptable column packing in terms of ball diameter and length of section packed with balls. Balls with diameters of 0.24, 0.28, 0.32, 0.40, and 0.48 cm were available for these tests with selected section lengths of 2.0, 2.7, 3.0, 6.0, and 8.0 cm.

The procedure used was as follows. Transducer E was mounted on the column and the controller for the vibration exciter set to sweep the excitation frequency from 35 Hz to 3 kHz at an arbitrary constant acceleration. Three swept-frequency response curves of transducer E output were generated on the oscilloscope screen and photographically recorded: (1) with the column empty of liquid, plates, etc., (2) with the column filled with 10-St dimethyl siloxane to the 11-cm level, and (3) with the column filled with dimethyl siloxane as in (2) and the plates, retainer tube, and plug in place (the plates separated by means of a spacer tube, since no balls were used). The curve from run (1) is the transverse vibrational response of transducer E. From the run (2) curve, the resonance frequency and damping characteristics of the basic system may be determined. Resonance was at 2.35 kHz, and the damping ratio approximately 0.03 of critical. The curve from run (3) shows a resonance frequency of 2.20 kHz and a damping ratio of 0.10 of critical, which was considered to be acceptable.

The experimental value of resonance frequency from run (2) is higher than the calculated value of 2.24 kHz obtained in 2.1.2. The difference may result from several sources, including an inexact knowledge of the bulk modulus for the 10-St dimethyl siloxane used and imprecision in the determination of resonance frequency. It is also possible that the theory is deficient. Another factor, not considered in the analysis of 2.1.2, that can affect the resonance frequency is the presence in the liquid of absorbed gases and other impurities. The presence of gases always results in a lowered resonance frequency, and the presence of impurities usually does.

Other swept-frequency response curves of transducer E output were then generated and recorded with various sized balls and various section heights. These tests showed that damping could be varied over a wide range (from very under damped to very over damped) and that, regardless of ball size, the resonance frequency is lowered significantly when either 6.0- or 8.0-cm section lengths are used. The probable reason for this lowered resonance frequency is that with these quantities of balls the volume available for liquid (filled to the 11-cm level) is

reduced enough to produce a significant reduction in the value of the effective bulk modulus, as discussed in 2.1.2.

Examples of the results obtained using 0.24-cm balls are shown in figure 4. With a ball section 3.0 cm in length, the pressure amplitude is seen to decrease with increased frequency (top trace), indicating that the calibrator system is overdamped. With a 2.0-cm section, the pressure amplitude is seen to rise to a maximum between 2.1 and 2.4 kHz (center trace), indicating that the column is underdamped (estimated to be 0.38 of critical). The most nearly flat response was obtained with the 2.7-cm section, for which the pressure amplitude is seen to remain almost constant to approximately 2.4 kHz (bottom trace). The small resonances near 1.1 and 1.4 kHz are believed to result from mechanical resonances of the column assembly, and data near these frequencies are not used.

As described in 3.3, reference transducer E was used in 16 calibrations of other transducers. In particular, 30 measurements were made with a constant acceleration of 20 g_n at two frequencies, 35 and 50 Hz, for which the output should be the same. Two computed values are also available. The data and statistics are given in table 2. The computed coefficient of variation of 1.1% is considered to demonstrate the acceptable repeatability of the source. Sources of both systematic and random errors are discussed in 3.2.

3. CALIBRATION

3.1 Calibration Procedure

Before calibration of a pressure transducer can be carried out using the source, the size of the contribution to zero shift from the transducer transverse acceleration response is checked. The transducer is mounted on the empty column, and the vibration exciter driven at the intended test level, usually 20 g_n zero-to-peak. For all transducers tested in the study, the transverse response was not significant, i.e., contributed to less than 0.02% of the transducer response.

For the calibration itself, the column must be loaded with balls and filled. The procedure is as follows:

1. Mount the transducer to be calibrated and the reference transducer (or, if not used, a plug) in the holes provided at the base of the column.

2. Position the restraining plates, steel balls, and retainer tube in the column.

3. Place the column in a suitable bell jar, as shown in figure 5. The bell jar should have a tube passing through its top and be equipped with a ball valve (Q).

4. Attach a suitable flask to the ball valve with the upper opening unstoppered. One type of suitable flask is a leveling bulb. The flask should have a volume of at least twice the volume of the empty column.

5. Close the valve.

6. Pour at least enough 10-St dimethyl siloxane into the flask to fill the empty column.

7. Connect the bell jar lower port and the upper opening of the flask to a mechanical vacuum pump and operate the pump until the liquid in the flask does not bubble (fifteen minutes is usually sufficient).

8. Open the valve until the column is filled approximately to the desired level; then close the valve.

9. Slowly release the vacuum in the bell jar.

10. Remove the column from the jar.

11. Mount the column on the armature of the vibration exciter.

12. Use a suitable depth micrometer to measure the liquid level. The lowest setting of the micrometer at which a drop of liquid adheres to the end of the micrometer probe is taken as the distance between the liquid surface and the top of the column.

13. Adjust the level by adding or removing a few drops with a suitable instrument, such as an eye dropper, until the desired level is attained.

14. Screw the threaded plug into the fixture and torque to the recommended value of from 16 to 19 N·m (12 to 14 pound-force ·ft). This completes the filling procedure.

Following filling, the controller of the vibration exciter is set to sweep the frequency of the driving signal from 35 Hz to 3 kHz at a given acceleration, usually 20 g_n zero-to-peak.

An acceleration of 36 g_n zero-to-peak is required to generate pressures of 34 kPa zero-to-peak with a 10-cm column of 10-St dimethyl siloxane. However, as 36 g_n zero-to-peak is close to the upper acceleration level capability of the vibration exciter with the column as load, and operation of the exciter at that level resulted in occasional over-travel alarms, the majority of the calibrations reported in this paper were made using an acceleration of 20 g_n zero-to-peak, resulting in pressures of 19 kPa zero-to-peak over the frequency range of 35 Hz to 3 kHz. One test was run at an acceleration of 36 g_n zero-to-peak over a frequency range of 50 Hz to 3 kHz to demonstrate the higher pressure capability of the method. In this test, the lower frequency limit of 50 Hz was imposed by the displacement limits of the armature of the vibration exciter.

During a dynamic calibration run, readings on the digital
voltmeter of the transducer outputs are recorded at selected fre-
quencies, and curves of transducer response vs frequency are re-
corded by photographing the oscilloscope display of the test (and
reference, if desired) transducer outputs as the fixture is vibrated
at a constant acceleration over the frequency range of interest.

Static calibrations of d-c responding transducers are made with
the transducer mounted in the liquid-filled fixture by imposing known
pneumatic pressures on the top of the liquid column and measuring the
resulting transducer output with the digital voltmeter. A liquid-
head correction is made. Static pressures are produced with a pre-
cision bellows and read with a dial gage.

3.2 Error Analysis

The dynamic pressure source provides capabilities not before
available. There is no "standard transducer" that can be used to
evaluate the source performance. The best that can be done is to
carry out repetitive measurements on a transducer for which theory
predicts that the frequency response should be flat beyond the fre-
quency range of interest. Such a series of measurements was carried
out with the piezoelectric quartz crystal reference transducer E;
the results are given in 2.4.3. Because there is no "standard trans-
ducer," it is instructive to analyze the potential sources of error.

Factors contributing to the uncertainty of the pressure avail-
able from the source include (1) uncertainty in the height of the
liquid column resulting from meniscus effects and from machining in-
accuracies, (2) uncertainty in the knowledge of the true density of
the liquid resulting from variations in temperature, (3) uncertainty
in the acceleration produced by the vibration exciter and measured
by its accelerometer, (4) uncertainties in various voltage measure-
ments, and (5) electrical noise. For the dynamic calibration as a
whole, uncertainty in the amount of transducer output resulting from
transverse vibrational response, additional voltage-measurement un-
certainties, and additional electrical noise should be added to the
uncertainties listed above. For static calibrations, uncertainty in
the knowledge of the additional pressure applied to the liquid in
the column must be considered.

Estimated values for these uncertainties are given in table 3.
The overall estimated uncertainty for dynamic calibration measurements
is $\pm4.1\%$ of the true value and for static calibration measurements
$\pm0.4\%$ of the true value.

3.3 Results from the Calibration of Six Transducers

Six pressure transducers were supplied by the project sponsor for
dynamic calibration using the dynamic pressure source. The character-

istics of these test transducers and of reference transducer E are given in table 4. Three of the transducers (A1, A2, and A3) are of the same model and have a silicon diaphragm into which a Wheatstone bridge circuit has been diffused. The other three (B, C, and D) are bidirectional unbonded strain-gage types. Reference transducer E, used as a control in all tests, is a piezoelectric quartz crystal transducer, as has been noted.

Three calibration runs each were made of transducers A1, A2, A3, C, and D using a 20 g_n zero-to-peak acceleration level from 35 Hz to 3 kHz. Transducer B was calibrated in only one run (calibration No. 10) and at a level of only 10 g_n zero-to-peak. The reason for the change in procedure was that transducer B was accidentally overranged in preliminary resonance tests and damaged as a result. After the damage had occurred, the output waveform of the transducer was distorted when full-scale sinusoidal pressure was applied. Calibration at approximately one-half the full-scale pressure was attempted and resulted in good waveform; therefore, calibration was completed at that level.* The test transducer and the reference transducer E outputs were monitored on an oscilloscope whose horizontal deflection system was driven by a swept-frequency sine-wave generator from 35 Hz to 3 kHz. In addition, the outputs were monitored with a digital voltmeter at 35, 50, 75, 100, 200, 300, and 400 Hz for all calibrations and at 500 Hz and 1, 1.5, 2, and 2.5 kHz for selected calibrations. Reference transducer E was included as a control in all 16 of the calibration runs.

The frequency-response curve for transducer A1, shown in figure 6A, is different from that of transducer E and shows evidence of overdamping. The curves for transducers A2 and A3 are similar. The manufacturer was asked to supply details of the design. It was reported that this model of transducer has a protective diaphragm 0.015-cm thick in front of the sensing diaphragm, with an air space of 0.015 to 0.033 cm between the two diaphragms. Small holes, 0.013 to 0.015 cm in diameter, around the periphery of the protective diaphragm admit the pressure to the sensing diaphragm. It seems likely that this arrangement significantly affects the damping characteristics of the transducer.

For a given transducer, it is expected that all measurements made at 35 Hz and 50 Hz would agree. For the three transducers A1, A2, and A3, the mean values of the six measurements (two measurements in each of the three calibration runs for each transducer) are 21.232, 21.483, and 23.427 mV rms, respectively. The maximum deviations from these means are 0.3%, 0.2%, and 0.7%, with sample standard deviations of 0.059, 0.031, and 0.111 mV rms. Comparison of the static calibration output measurement with the above mean values showed differences of 3.7%, 2.9%, and 2.4% for transducers A1, A2, and A3, respectively. The data are given in table 5.

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*The oscilloscope trace shown in figure 6B was recorded using an acceleration of 18 g_n zero-to-peak before the damage occurred. (18 g_n gives full-scale pressure variations for this transducer.)

Figures 6B, 6C, and 6D are of the frequency response curves for transducers B, C, and D. The mean values of the six measurements made at 35 Hz and 50 Hz for transducers C and D are 10.67 and 3.550 mV rms, respectively. The maximum percent deviations from these means are 0.4% and 0.8%, with sample standard deviations of 0.027 and 0.015 mV rms. No statistics are given for transducer B, which was calibrated in only one run. Comparison of the static calibration output measurement with the above mean values showed differences of 2.6% and 2.4% for transducers C and D, respectively. Comparison of the mean of the two measurements at 35 Hz and 50 Hz for transducer B with the static calibration output measurement for this transducer showed a difference of 0.8%. These reported differences between static and low-frequency dynamic calibrations probably result from the uncertainties involved in determining the height of the liquid column. It is not possible to perform a static calibration on reference transducer E, as this transducer has no response to static pressure.

If the test transducer natural frequency is high, the undamped resonance frequency of the source-transducer combination will not be appreciably affected: this is the case for transducer A1 (and A2 and A3), as is shown by the frequency-response curve in figure 7A. The vertical axis scale (transducer output) is arbitrary. If the test transducer natural frequency is relatively low, as it is for transducers B, C, and D (3.5 kHz, 5 kHz, and 8.5 kHz, respectively), the calibrator system resonance will be lowered. The frequency-response curves in figures 7B, 7C, and 7D show the resonance frequency of the source-transducer combination as being about 1.3, 1.7, and 2.2 kHz, respectively. These curves and values were obtained with the column filled with dimethyl siloxane only, balls and plates having been removed. For calibrations of transducers with low natural frequencies, not only is the resonance frequency lowered, but the degree of damping is also altered; 0.28-, 0.32-, and 0.48-cm-diameter balls were required for transducers B, C, and D, respectively, when the length of the section of balls was held to 2.7 cm. (For transducer B, it appears that balls of about 0.44-cm diameter would have given a more uniform response but were not available; the height of the section of balls could have been changed but for the sake of consistency was not.)

Consideration of test transducer natural frequencies is useful in an evaluation of transducer dynamic performance as shown in curves such as those of figure 6. Pressure transducers are commonly not used to measure pressures varying at frequencies beyond approximately 20% of the natural frequency of the instrument. For transducers B, C, and D, this 20% limit is approximately 700 Hz, 1.0 kHz, and 1.7 kHz, respectively. As may be seen by examination, the response of transducers C and D is reasonably flat up to their respective limits. The response of transducer B up to its 20% limit is somewhat less flat.

In a final experiment, the output of the reference transducer was both recorded and used to provide an input signal for the controller for the vibration exciter with the power to the exciter continuously adjusted to maintain the reference transducer output at a constant level.

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The output of the test transducer under these conditions was recorded. A plot is shown in figure 8 for transducer B. The curve suggests agreement with the manufacturer's specified natural frequency of 3.5 kHz and should represent the frequency response of the transducer with no interpretation required. Further work is required to validate this technique.

4. CONCLUSIONS

The useful frequency range of the liquid-column sinusoidal pressure calibration source has been increased considerably by damping the liquid column. The use of steel balls with 10-St dimethyl siloxane liquid to achieve this damping is simpler and more versatile than other damping schemes considered. The result is a dynamic pressure source capable of generating pressure levels of up to 34 kPa over a frequency range from approximately 50 Hz to 2 kHz, flat to within +5%. At frequencies below 50 Hz the pressure amplitude is limited by the displacement capability of the vibration exciter used. The estimated total calibration measurement error using the source with a typical transducer is +4.1%.

It is important to note that a flat frequency response can be achieved over a frequency range of up to a maximum of about 80% of the natural frequency of the liquid column-transducer combination, and that this natural frequency is lower than that of the component with the lowest natural frequency.

The wetted surface area required to damp adequately a particular liquid column and transducer combination is dependent on the natural frequency of the combination. Combinations with high natural frequencies require larger wetted surface areas than those with low natural frequencies. The wetted surface area may be adjusted easily by changing ball size, ball quantity, or both.

Over a frequency range of up to 20% of the resonance frequency of the liquid-column transducer combination, the dynamic pressure source provides an absolute calibration to within 5% of the true pressure supplied in the sense that this pressure is calculable on the basis of mechanical parameters that can be measured and on the basis of knowledge of the acceleration imparted to the column, which acceleration can be measured with instruments that may be traced in calibration to basic standards. For the remainder of the frequency range, a reference transducer with a flat response over that range is required both for setting and monitoring the degree of damping.

Another calibration technique using the source has been the subject of several experiments and requires further development. In this technique, a signal derived from the reference-transducer output is supplied as a control input to the vibration-exciter control, and the acceleration of the column is continuously adjusted to maintain the pressure amplitude at a constant level as the frequency is swept over the desired range. In principle, the only frequency limitations should be

imposed by the frequency responses of the reference transducer and the exciter system.

5. RECOMMENDATIONS

The following recommendations for future work are based on the experience gained during the development of the dynamic pressure source and during the various calibrations.

1. A number of different high-natural-frequency, flush-diaphragm pressure transducers should be calibrated with the dynamic pressure source to determine if the degree of damping is approximately constant.

2. The number and size of balls should be more widely varied and curves generated showing the relationship between these parameters and column resonance frequency and damping characteristics.

3. The effect of temperature changes on the degree of damping should be investigated.

4. Calibrations using the source should be attempted on transducers with low natural frequencies, with a constant-level-control servo used to maintain the reference transducer output constant with frequency. This technique should be developed and validated.

5. The use of columns with larger bores to reduce the percent contribution of dV_t (see 2.1.2) should be investigated. This recommendation is particularly aimed at calibrations of transducers with large dV_t values, usually transducers with low natural frequencies.

6. The use of short columns (with high resonance frequencies) should be investigated without damping over a frequency range of up to 20% of the resonance frequency of the column-transducer combination.

7. The presence of the retainer tube used to transmit force from the threaded plug to the upper plate has been found to complicate measurement of the height of the liquid column. A modified design eliminating the retainer tube would be desirable. It has been suggested that the upper plate could itself be threaded into the bore.

8. Any new columns should be fabricated without the flats machined near the base into which the transducer mounting holes are bored. The presence of the slots formed by the flats reduces column stiffness.

9. The discrepancy between the theoretical predictions for natural frequency and the experimental values achieved requires further examination. Experiments with several fluids, dimensions, and degrees of damping should provide data for further analysis.

6. ACKNOWLEDGEMENTS

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TABLE 1

Working Liquids Used in Preliminary Investigations of Damping

Liquid	Viscosity (St)	Density (kg/m³)	Bulk Modulus (Pa)	Velocity of Sound (m/s)	Advantages	Disadvantages	Column Description — I.D. (cm)	Height (cm)	Material	Experiments — Damping	Amplitude Ratio*
Water	0.009	1.00×10^3	20.9×10^9	1460	High bulk modulus, and velocity of sound; non-toxic; inexpensive	Low viscosity; high vapor pressure; corrosive to steel	2.2	35	Brass	Smooth wall	14
							1.3	35	Brass	Smooth wall	12
							1.3	35	Copper	Spiral fins	15
							1.2	35	Brass	Woven-metal mesh filter	8.0
								35	Copper	Multiple channels	9.0
								35	Copper	Interlacing fins	**
Tetrabromo-ethane	0.080	2.95×10^3	29.3×10^9	1007	High density; non-toxic	Low viscosity; high vapor pressure; corrosive to steel, aluminum and other metals and rubber	2.2	35	Brass	Smooth wall	5.0
							1.2	35	Brass	Woven-metal mesh filter	**
							1.2	35	Brass	Sintered-metal filter	**
								35	Copper	Multiple channels	3.7
Fluorocarbon	0.026	1.88×10^3	9.8×10^9	730	High density; non-toxic	Low viscosity; low bulk modulus	2.2	35	Brass	Smooth wall	9.0
Mercury	0.001	13.6×10^3	265×10^9	1410	High density, bulk modulus, and velocity of sound	Low viscosity; dissolves most metals, health hazard	1.1	5	Stainless steel	Smooth wall	5.0
Glycerine	7.50	1.26×10^3	44.8×10^9	1904	High viscosity, bulk modulus, and velocity of sound; non-toxic	Hygroscopic	0.5	10	Brass	Smooth wall	5.2
Petroleum Oils	0.5 @25°C	0.86×10^3	15.2×10^9	1340	High viscosity and velocity of sound	Low density; viscosity temperature dependent	2.2	35	Brass	Smooth wall	16
							2.2	35	Brass	Woven-metal mesh filter	3.8
								35	Copper	Multiple channels	4.5
	15 @25°C						2.2	35	Brass	Smooth wall	12
								35	Copper	Multiple channels	1.1
Dimethyl	600	0.97×10^3	9.28×10^9	987	High viscosity; non-toxic	Low bulk modulus and density	2.4	10	Brass	Smooth wall	13
							1.1	10	Brass	Smooth wall	8.0
							0.50	10	Aluminum and glass	Smooth wall	3.3
	300						2.4	10	Brass	Smooth wall	13.0
	125						2.4	10	Brass	Smooth wall	20
	10						2.4	10	Brass	Smooth wall	33
							1.1	10	Brass	Smooth wall	27
							0.50	10	Aluminum and glass	Smooth wall	7.4
							0.40	10	Aluminum and glass	Smooth wall	2.8
							0.20	10	Aluminum and glass	Smooth wall	1.4
							0.15	10	Aluminum and glass	Smooth wall	**
							0.16	10	Brass	Multi-tube fixture	Response flat to ±5% from 40 Hz to 750 Hz

*For a given value of acceleration, amplitude ratio is here defined as the ratio of measured maximum amplitude (at resonance) to the average of the amplitudes measured over 35-50 Hz.

**Data not obtainable.

TABLE 2

Reference Transducer E Output*
(mV rms)

Frequency (Hz)	Calibration Number															
	1	2	3	4	5	6	7	8	9	10**	11	12	13	14	15	16
35	18.14	18.16	18.10	17.76	17.72	17.73	17.71	17.58	17.65	17.86	18.12	18.12	18.17	17.88	17.83	17.81
50	18.21	18.06	18.07	17.76	17.76	17.78	17.73	17.52	17.71	17.92	18.08	18.11	18.09	17.92	17.88	17.83
100	18.22	18.01	18.02	17.82	17.85	17.84	17.73	17.61	17.79	17.92	18.07	18.05	18.08	17.91	17.88	17.83
200	18.23	18.10	18.08	17.97	17.95	17.95	17.83	17.72	17.89	18.24	18.27	18.27	18.27	18.03	18.02	18.02
300	18.24	18.09	18.13	18.00	18.00	17.97	17.88	17.90	17.90	18.72	18.36	18.38	18.37	18.16	18.15	18.09
400	18.28	18.11	18.12	18.10	18.10	18.04	17.96	18.02	18.02	19.24	18.35	18.35	18.36	18.45	18.42	18.41
500			18.04									18.41				
1000			18.50									17.38				
1500			19.06									12.89				
2000			19.03									8.16				
2500			18.00													

It would be expected that the frequency response would be flat over the range from 35 through 50 Hz. The statistics of the 30 measurements and 2 computed values of transducer E output at these frequencies is as follows: sample mean, 17.9 mV; sample standard deviation, 0.19 mV; coefficient of variation (1 S%), 1.1%; and maximum deviation (scatter), +0.31 mV (+1.7% of mean), -0.38 mV (-2.1% of mean).

*The conditions of measurement were as follows, except as noted: liquid used, 10-St dimethyl siloxane with a density of 0.971 gm/cm^3; column height, 10 cm above the center of transducer diaphragm; and acceleration, 20 g_n zero-to-peak.

**Calibration 10 was conducted at an acceleration of 10 g_n zero-to-peak, as explained in the text. The values given here are computed.

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TABLE 3

Factors Contributing to Transducer Calibration Error [a]

Factor	Systematic Error (% of measured value)	Random Error (% of measured value)
DYNAMIC		
Liquid Column		
Height of liquid column	±0.1	±1.0
Variation of liquid density with temperature	—	±0.2 [b]
Acceleration Applied		
Calibration of exciter control accelerometer with reference accelerometer and precision of reading	±1.0	±0.1 [c]
Transducer Output		
Voltmeter calibration of precision of reading	±0.3 [d]	±0.05 [e]
Noise	—	±0.1 [f]
Transverse acceleration response of transducer	±0.02 [g]	—
TOTAL RMS	±1.05	±1.03

Estimated Error = RMS systematic + 3 RMS random = ±4.14%

Factor	Systematic Error (% of measured value)	Random Error (% of measured value)
STATIC		
Pressure Applied		
Pressure gage calibration and precision of reading	±0.07 [h]	±0.06 [i]
Transducer Output		
Voltmeter calibration and precision of reading	±0.07 [j]	±0.03 [k]
Noise	—	±0.07 [l]
TOTAL RMS	±0.099	±0.097

Estimated Error = RMS systematic + 3 RMS random = ±0.39%

[a] Typical calibration values for the source are acceleration, 20 g_n zero-to-peak and liquid column height above centerline of transducer, 10 cm using 10-St dimethylsiloxane with a bulk modulus of 9.47 x 10^8 m³/Pa.

[b] Estimate based on manufacturer's value of 0.098%/°C and variation of ±2°C.

[c] Estimate based on least count of ±1 mV for measurement of 1000 mV.

[d] Manufacturer's value for range of 20 mV.

[e] Estimate based on least count of ±0.01 mV for measurement of 20 mV.

[f] This figure corresponds to ±0.02 mV for a typical calibration.

[g] This value represents a maximum value for any of the transducers listed in table 4.

[h] Manufacturer's value for range of 17 kPa (5 psi).

[i] Estimate based on least count of ±0.2 kPa (±0.03 psi) for measurement of 17 kPa.

[j] Manufacturer's value for range of 30 mV.

[k] Estimate based on least count of ±0.1 mV for measurement of 30 mV.

[l] This figure corresponds to ±0.02 mV for a typical calibration.

TABLE 4

Transducer Characteristics*

Transducer	Type	Range (kPa zero-to peak)	Natural Frequency (kHz)	Diaphragm Diameter (cm)	Full-Range Deflection of Diaphragm at Center** (cm)
A-1,A-2,A-3	Silicon diaphragm with bonded Wheatstone bridge	34	45	0.22	2.5×10^{-4}
B	Unbonded straingage	17	3.5	1.26	3.8×10^{-4}
C	Unbonded straingage	34	5.0	1.26	3.8×10^{-4}
D	Unbonded straingage	102	8.5	1.26	3.8×10^{-4}
E (Reference)	Piezo-electric quartz crystal	54,400	100	0.953	Data not available from manufacturer

*From manufacturer's data.

**The manufacturers specify these deflections as maximum values.

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TABLE 5

Transducer Experimental Calibration Data*

Transducer Output
(mV rms)

Frequency (Hz)	Transducer A-1			Transducer A-2			Transducer A-3			Transducer B†	Transducer C			Transducer D		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
35	21.29	21.26	21.20	21.50	21.45	21.44	23.51	23.32	23.46	17.35	10.68	10.69	10.62	3.579	3.547	3.547
50	21.30	21.16	21.18	21.51	21.49	21.51	23.54	23.26	23.47	17.63	10.65	10.69	10.66	3.540	3.546	3.540
100	21.23	21.08	21.01	21.53	21.55	21.56	23.51	23.34	23.56	17.91	10.63	10.66	10.73	3.531	3.532	3.541
200	21.10	21.02	21.01	21.59	21.55	21.55	23.53	23.40	23.57	17.93	10.61	10.62	10.61	3.510	3.520	3.515
300	20.89	20.79	20.74	21.41	21.39	21.36	23.41	23.26	23.40	18.06	10.63	10.64	10.62	3.515	3.509	3.520
400	20.61	20.49	20.52	21.38	21.35	21.29	23.31	23.12	23.35	17.89	10.61	10.63	10.62	3.499	3.438	3.495
500			20.13									10.70				
1000			18.88									11.30				
1500			17.38									12.44				
2000			15.78									14.41				
2500			13.61													
Dynamic△ Sensitivity (mV/V/kPa)		0.158			0.160			0.174		0.260		0.158			0.053	
Static Sensitivity (mV/V/kPa)		0.153			0.155			0.170		0.258		0.154			0.054	
Sensitivity Ratio (Dynamic to Static)		1.037			1.029			1.024		1.008		1.026			0.976	

*The pressure supplied by the source for these calibrations was 19 kPa zero-to-peak; transducer excitation was 10 V dc. The values for transducers A-1, A-2, and A-3 are measured values; the values for transducers B, C, and D are values computed on the basis of the reference transducer (E) output.

†Only one calibration made; transducer was damaged after first calibration.

△From average of output values for 35 to 50 Hz.

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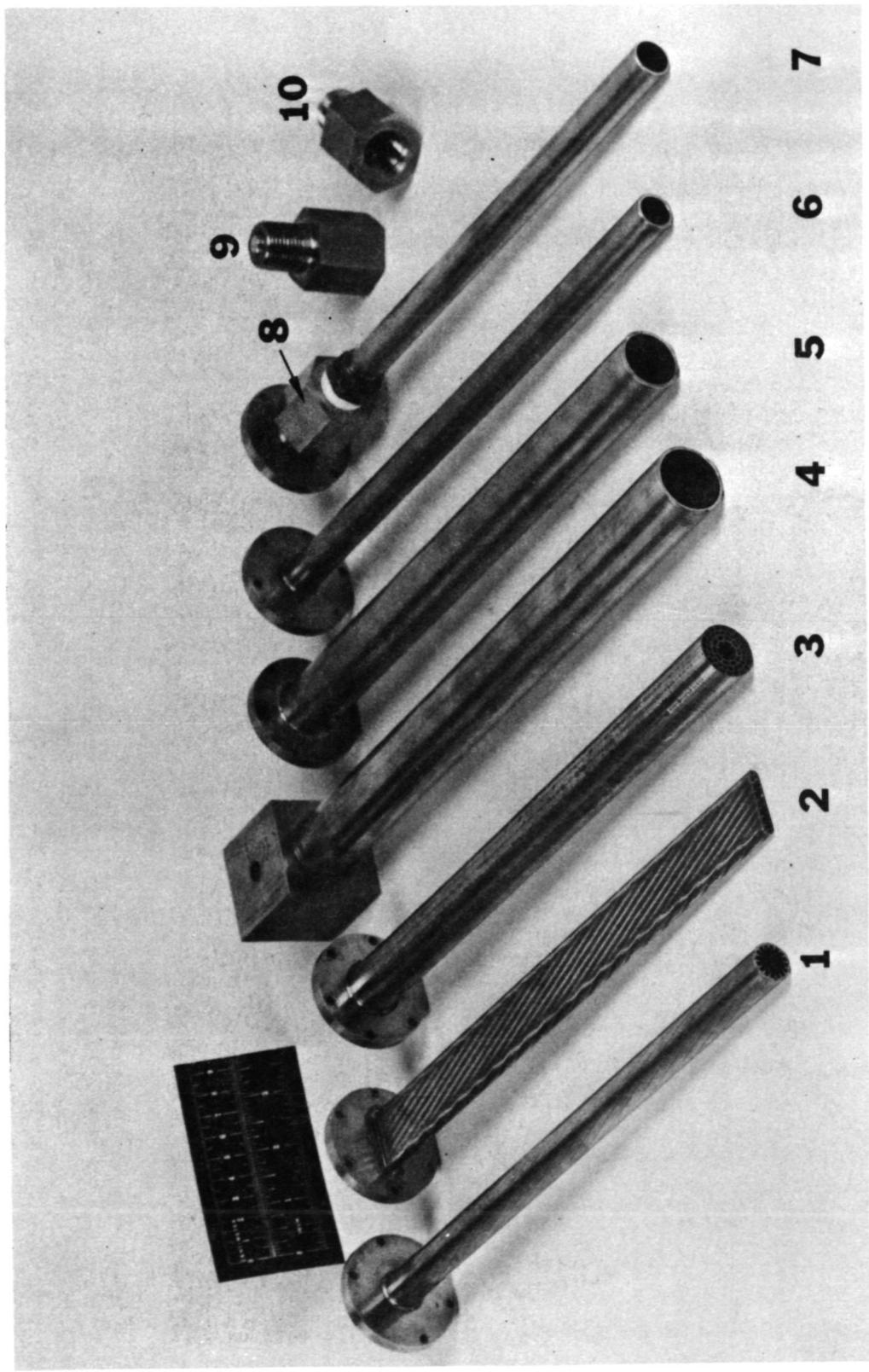
Figure 1: Columns and filters of various geometries used in preliminary experiments. Shown are tube with spiral fins (1); tube with diagonal fins (2); multi-channel tube (3); smooth-bore tubes (4), (5), and (6); smooth-bore tube (7) with woven-metal-mesh filter at (8); and sintered-metal filters (9) and (10).
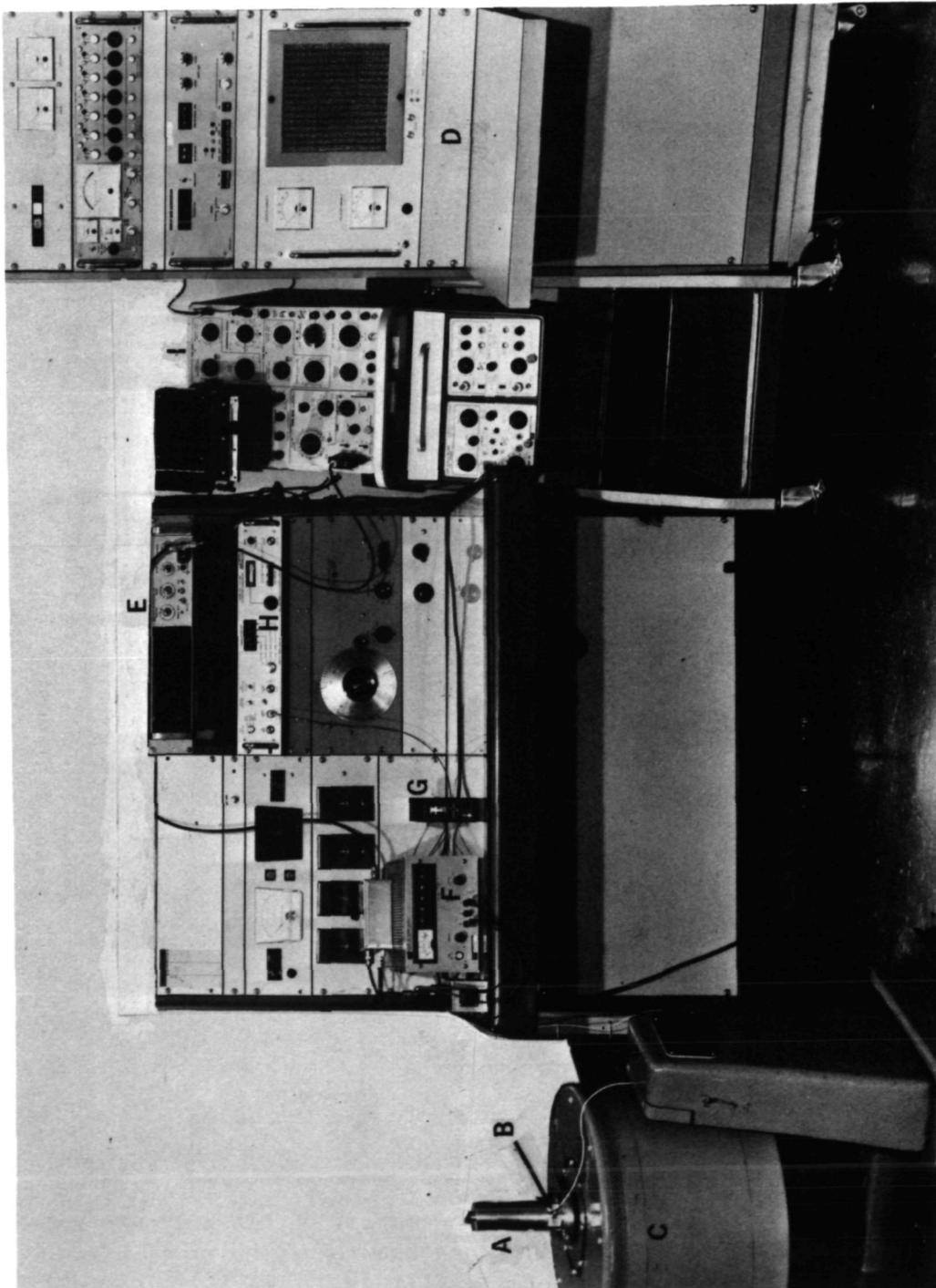
Figure 2: The dynamic pressure source in use to calibrate a pressure transducer. Shown are source (A) with reference transducer (B), vibration exciter (C), controller console (D) for vibration exciter, digital voltmeter (E), transducer power supplies (F,G), amplifier (H) for accelerometer used to monitor vibration exciter, and oscilloscope (I). The test transducer is hidden behind the source.

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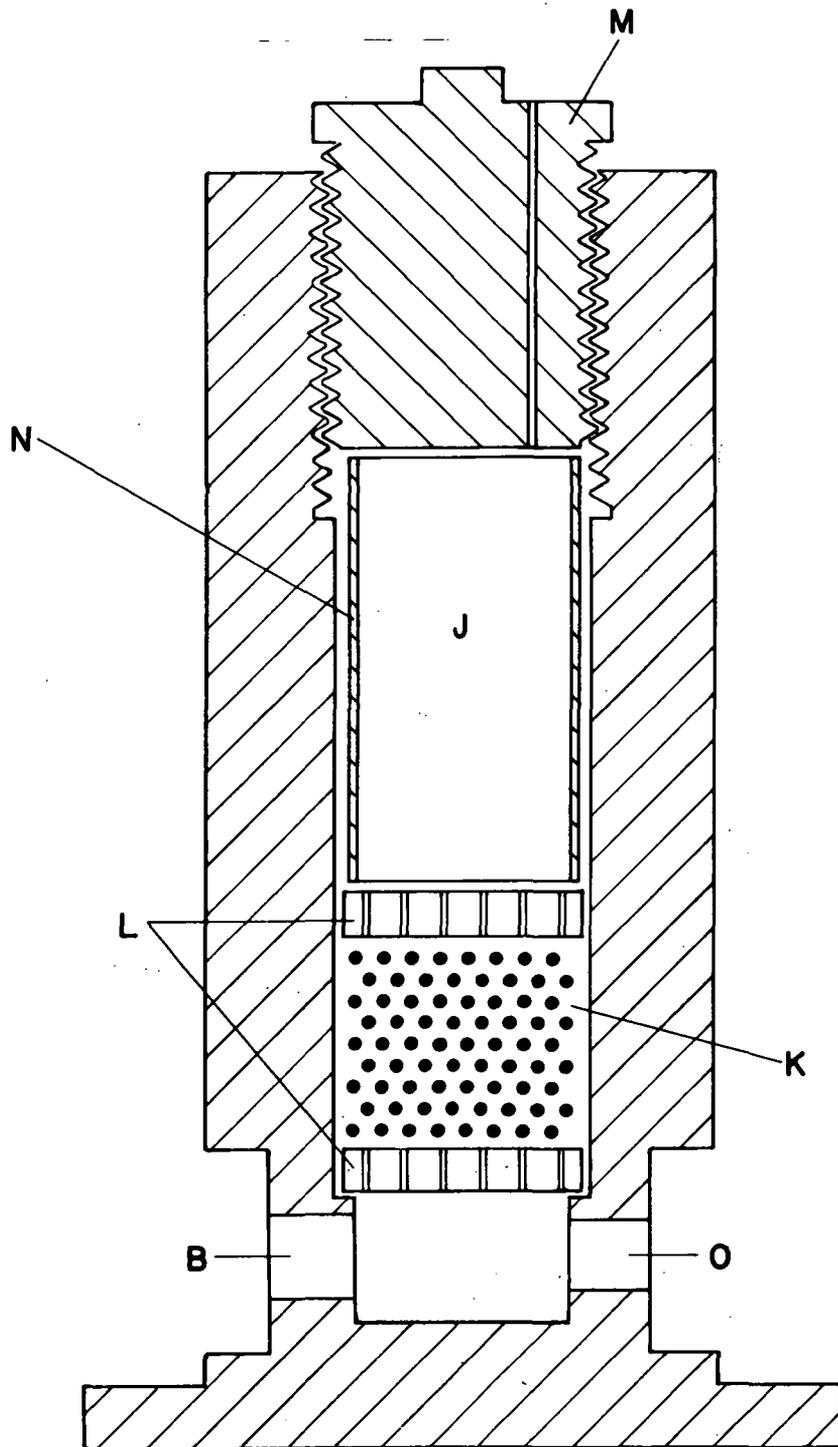
Figure 3: Cross section of dynamic pressure source. Shown are reference transducer port (B), liquid-column chamber with 1.7-cm-diameter bore (J), steel balls (K), pierced steel plates (L), threaded plug (M) with vent, retainer tube (N), and test transducer port (O).
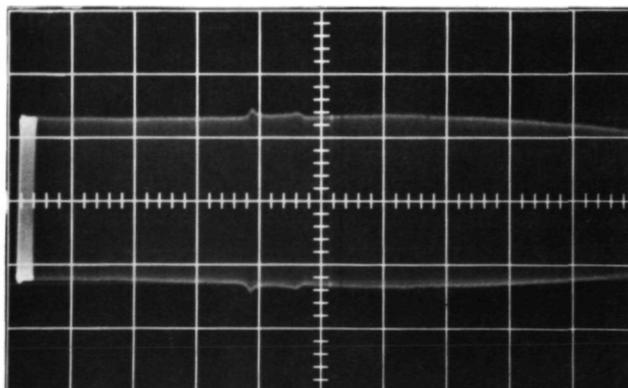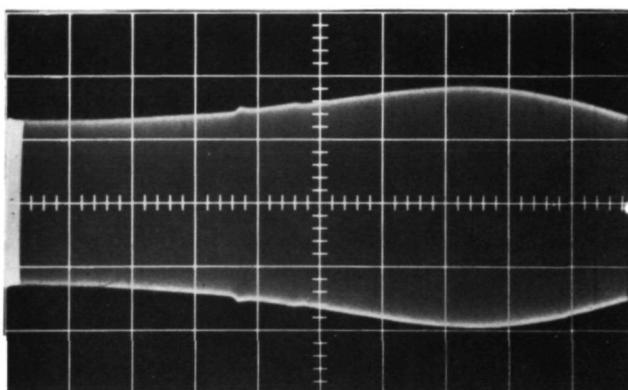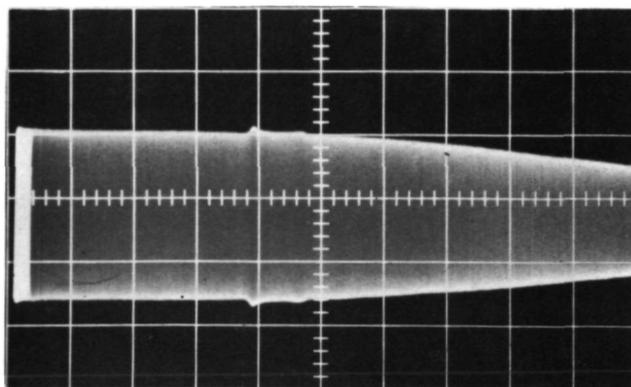
Figure 4: Oscilloscope traces showing peak-to-peak output (mV) from reference transducer E as a function of frequency (kHz) for three quantities of balls, as described in the text. The top trace shows the source-transducer combination as being overdamped; the center trace, underdamped; and the bottom trace, near optimum damping. The vertical scale is 20 mV peak-to-peak per division, and the horizontal scale is 0.3 kHz per division. The left-hand edge of each trace begins at 35 Hz; the sweep range is 3 kHz.
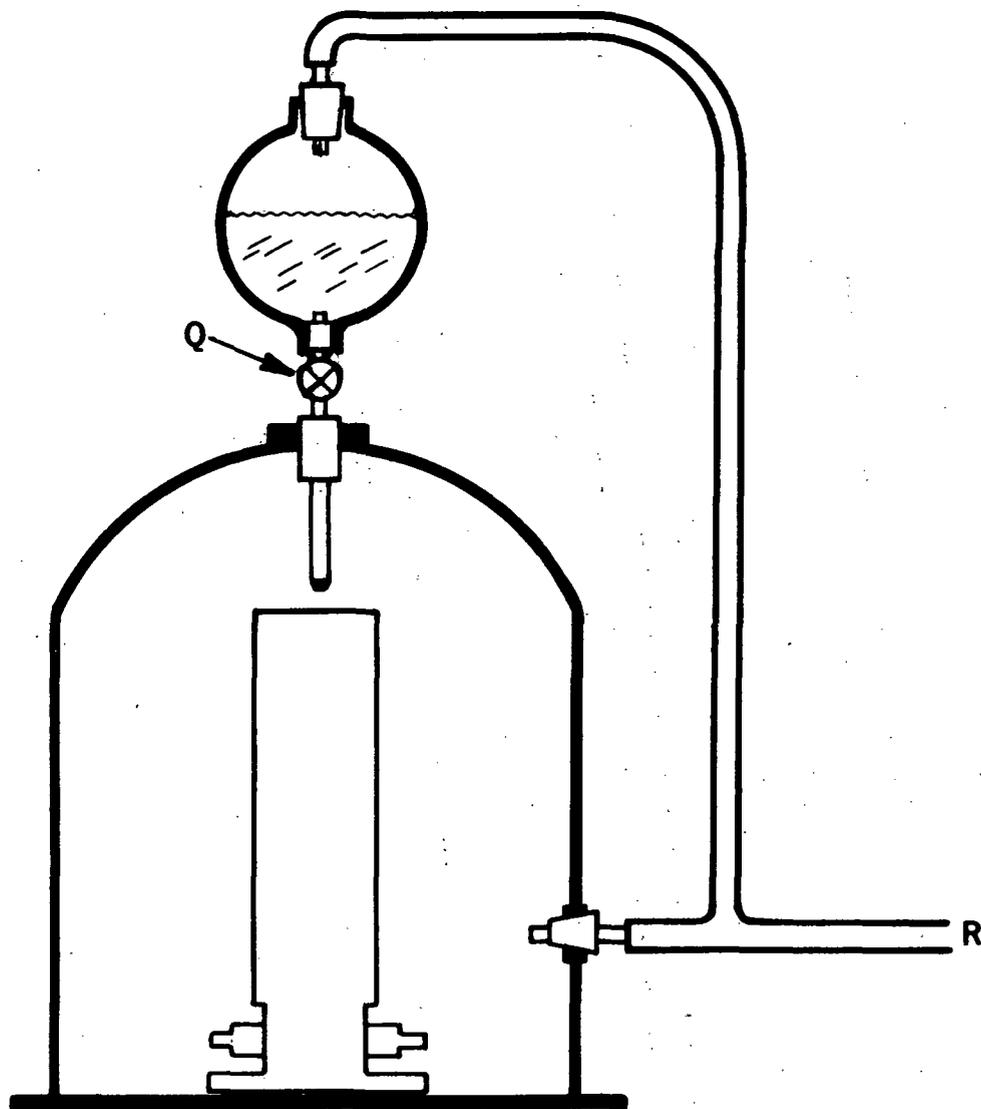
Figure 5:   Schematic of apparatus used to fill the source with liquid
under a weak vacuum. Q is a ball valve in the line between
bell jar and flask. Line R is connected to a source of vacuum.
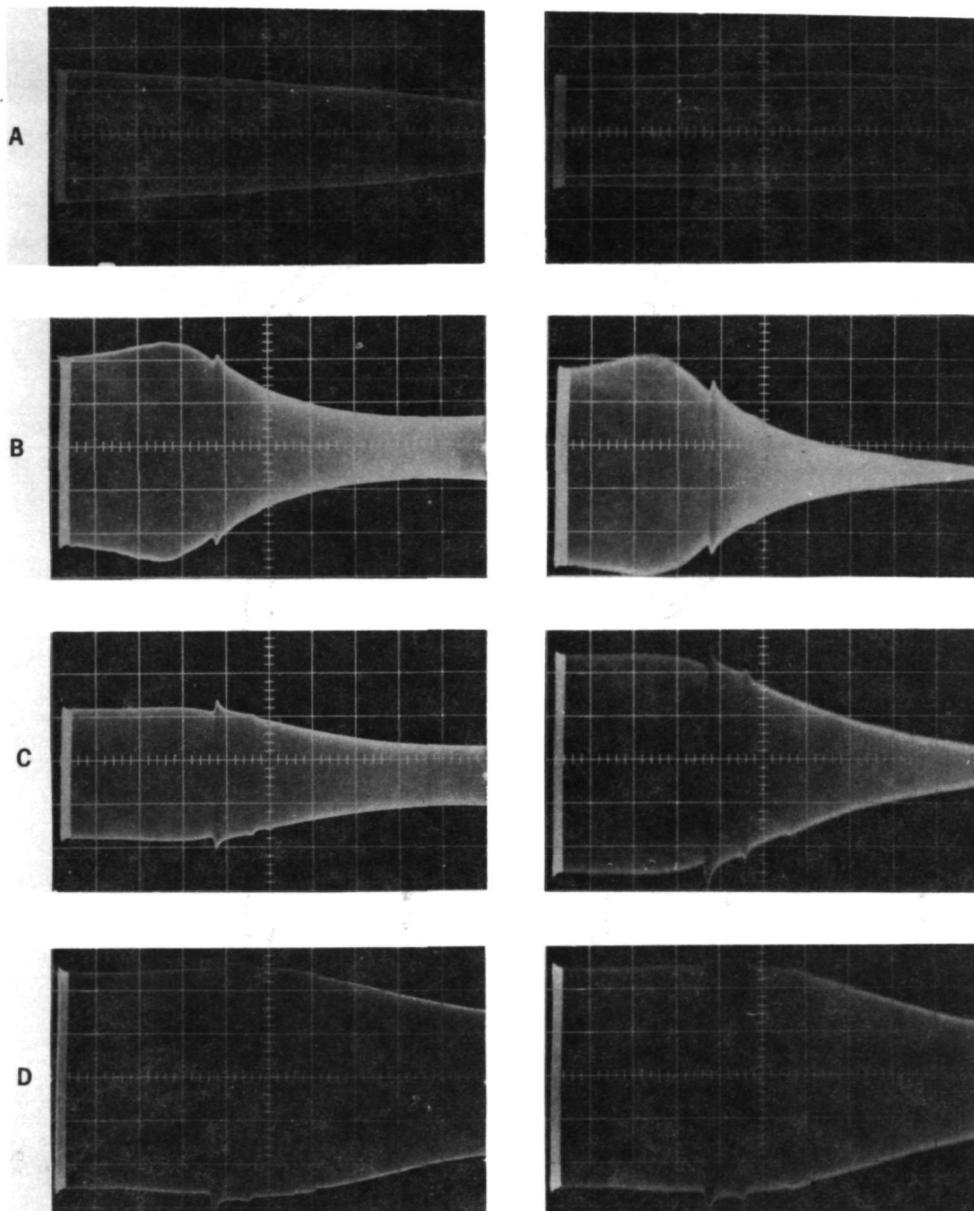
Figure 6:   Oscilloscope traces showing corresponding frequency-response
curves for test transducer (left) and reference transducer E
(right). Of interest is the frequency range over which
transducer output is at a relatively constant level. Trace A:
test transducer A-1; vertical scale for both transducers is
20 mV, peak-to-peak, per division. Trace B: test transducer
B; vertical scale for both transducers is 10 mV, peak-to-peak,
per division. Trace C: test transducer C; vertical scale for
both transducers is 10 mV, peak-to-peak, per division. Trace
D: test transducer D; vertical scale for D is 2 mV, peak-to-peak,
per division and for E, 10 mV, peak-to-peak, per division. The
horizontal scale for all traces is 0.3 kHz per division.

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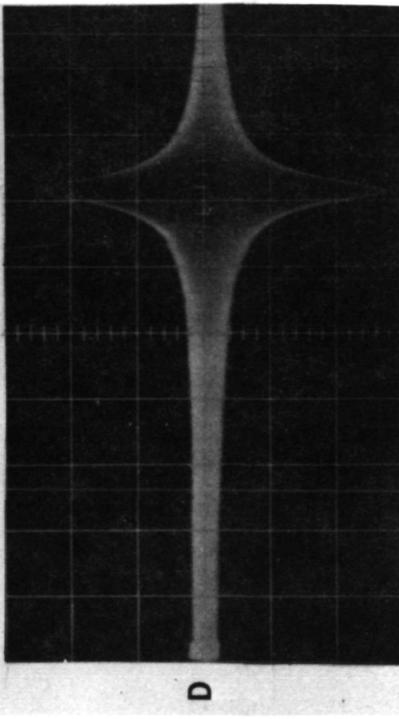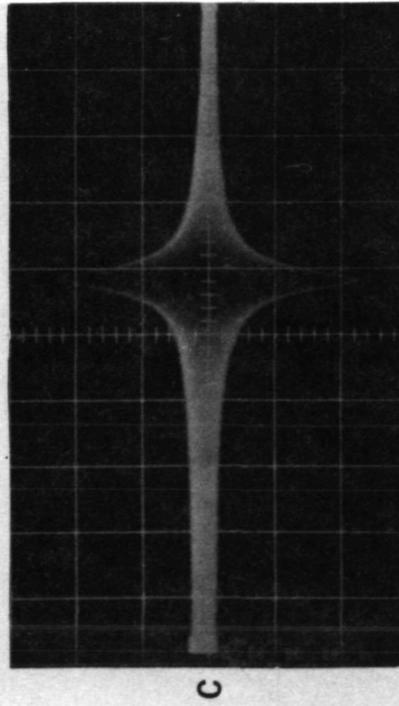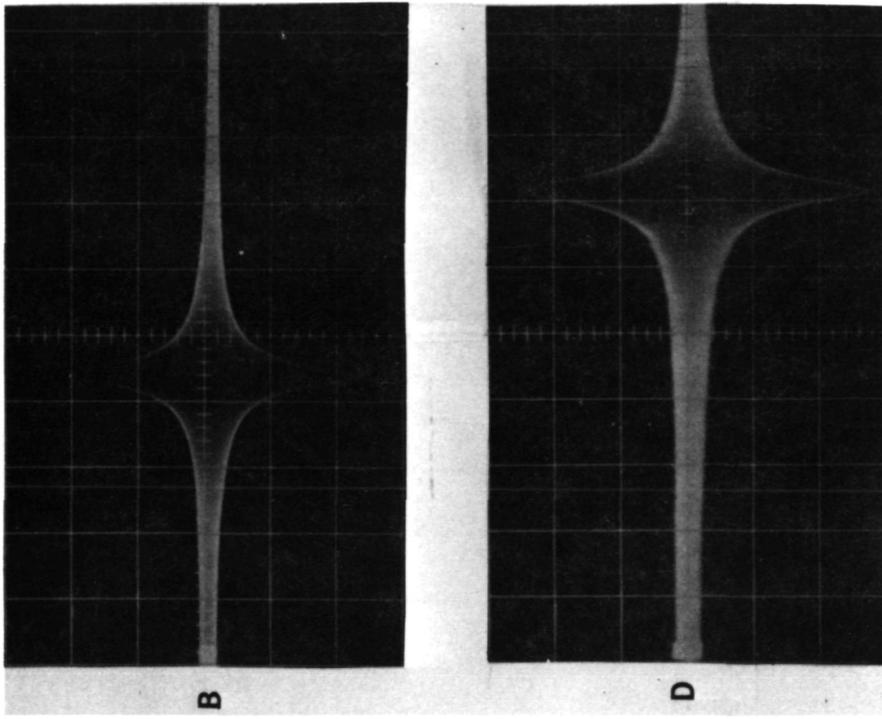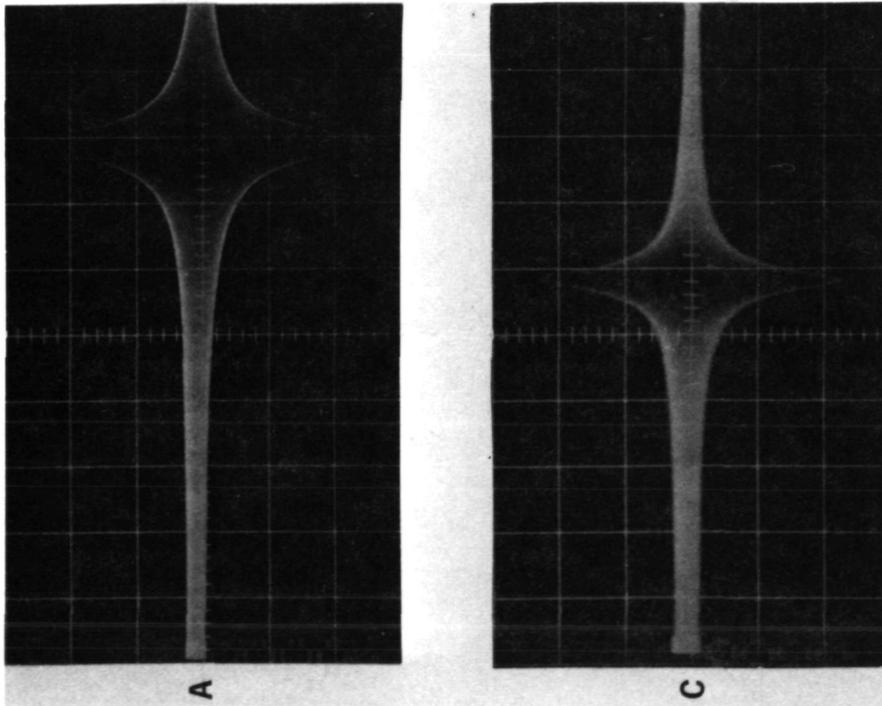
Figure 7: Oscilloscope traces showing frequency-response curves for the undamped source with test transducer A-1 (trace A), B (trace B), C (trace C), and D (trace D). Of interest are the respective natural frequencies. The vertical scale is reference transducer E output in arbitrary units; the horizontal scale is 0.3 kHz per division. The left-hand edge of each trace begins at 35 Hz; the sweep range is 3 kHz.

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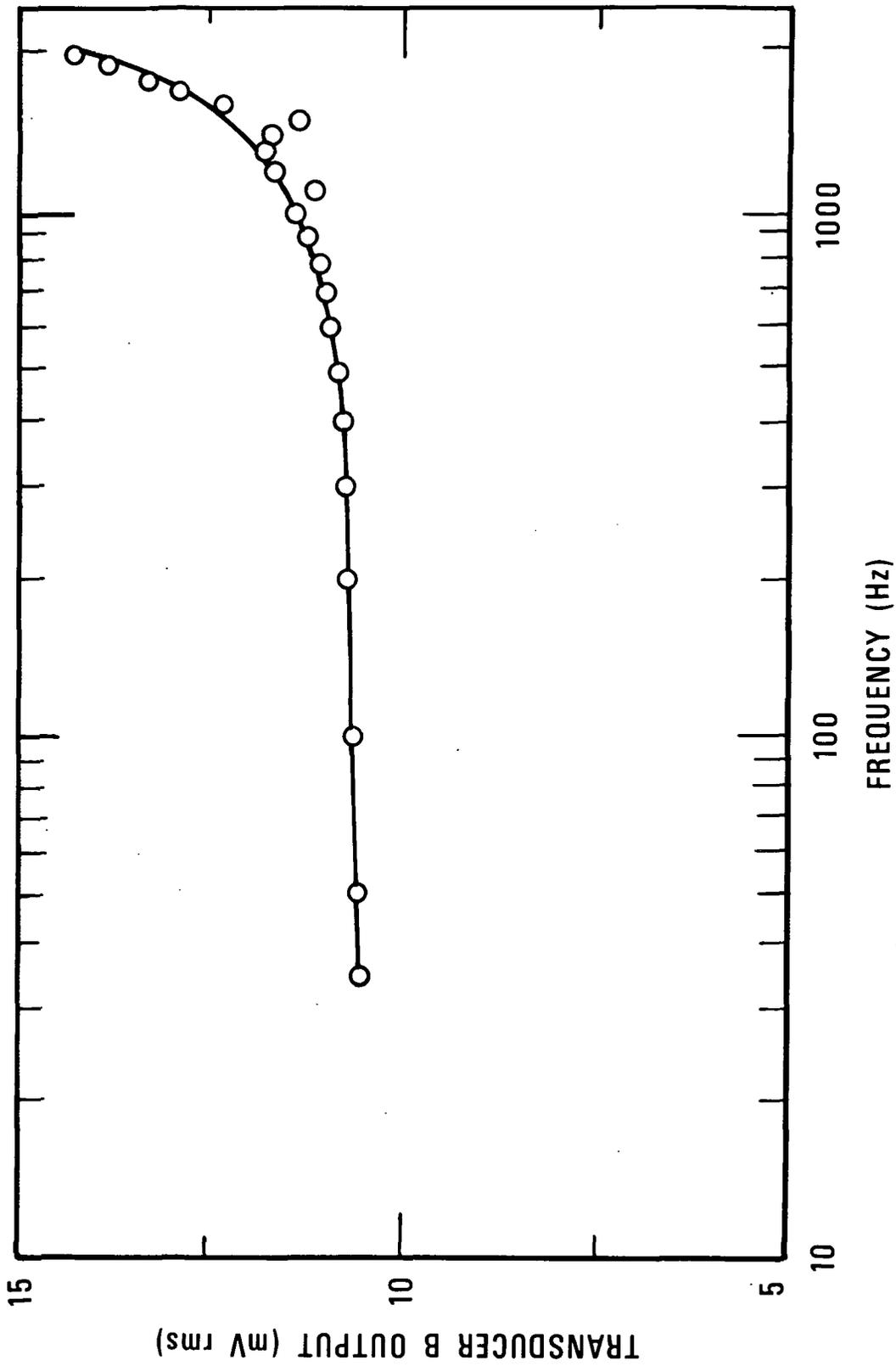
Figure 8: Test transducer B output (mV rms) as a function of frequency (log Hz) with the pressure level held constant, as described in the text. This plot should represent the true frequency response of transducer B.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A dynamic pressure source is described for producing sinusoidally varying pressures of up to 34 kPa zero-to-peak, over the frequency range of approximately 50 Hz to 2 kHz. The source is intended for the dynamic calibration of pressure transducers and consists of a liquid-filled cylindrical vessel, 11 cm in height, mounted upright on the armature of a vibration exciter which is driven by an amplified sinusoidally varying voltage. The transducer to be calibrated is mounted near the base of the thick-walled aluminum tube forming the vessel so that the pressure-sensitive element is in contact with the liquid in the tube. A section of the tube is filled with small steel balls to damp the motion of the 10-St dimethyl siloxane working fluid in order to extend the useful frequency range to higher frequencies than would be provided by an undamped system.

The dynamic response of six transducers provided by the sponsor was evaluated using the pressure sources; the results of these calibrations are given.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Calibration; dynamic; dynamic calibration; dynamic pressure; dynamic pressure source; liquid column; pressure; pressure source; pressure transducer; sinusoidal pressure; transducer.

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